The Variation of Ionisation with Velocity for the β-Particles.

By W. Wilson, M.Sc., Honorary Fellow of the University of Manchester.

(Communicated by Prof. E. Rutherford, F.R.S. Received February 18,—Read March 23, 1911.)

Although many researches have been made on the properties of the β-rays, no results have so far been published giving the variation of the ionisation due to them with their velocity. Durack* has shown that the β-rays from radium are less efficient ionisers than the cathode rays from a discharge tube, but no law of variation can be formulated from his experiments. A determination of this variation is of importance, since most experiments with the β-rays, *e.g.* those dealing with their absorption by matter, have been made by measuring the ionisation in a vessel through which the β-particles were passing, and such experiments do not give definite information about the actual number of particles involved unless the variation of the ionisation of the β-particles with velocity is known.

The following experiments have been made with a view of finding this relation, and the results show that the ionisation per centimetre of path is inversely proportional to the square of the velocity of the particles.

The method adopted was to separate out rays of different velocities by means of a magnetic field from the heterogeneous beam given out by Radium B and C. The charges carried by the particles of each velocity and the corresponding ionisations were measured, and the relative ionisation per particle at different velocities thus determined.

Apparatus.

The arrangement of apparatus used in the measurement of the first of these quantities is shown in fig. 1.

The source of radiation was a quantity of radium emanation (corresponding to about 150 milligrammes radium bromide) contained in a thin-walled bulb A which was fixed in position by means of a ground glass joint B. The rays passed into a flat brass box C, fixed between the pole pieces of an electromagnet, were bent round by the magnetic field, and entered the copper vessel E. The screens and walls of the vessel C were covered with cardboard in order to reduce the effects due to the secondary and scattered rays. The walls of E were so thick (2·5 mm.) as to be able to absorb any β-particles which fell on them. The length of E was 4 cm. and its diameter 3·3 cm.

---

* 'Phil. Mag.,' VI, 4, 1902, p. 29; and VI, 5, 1903, p. 550.

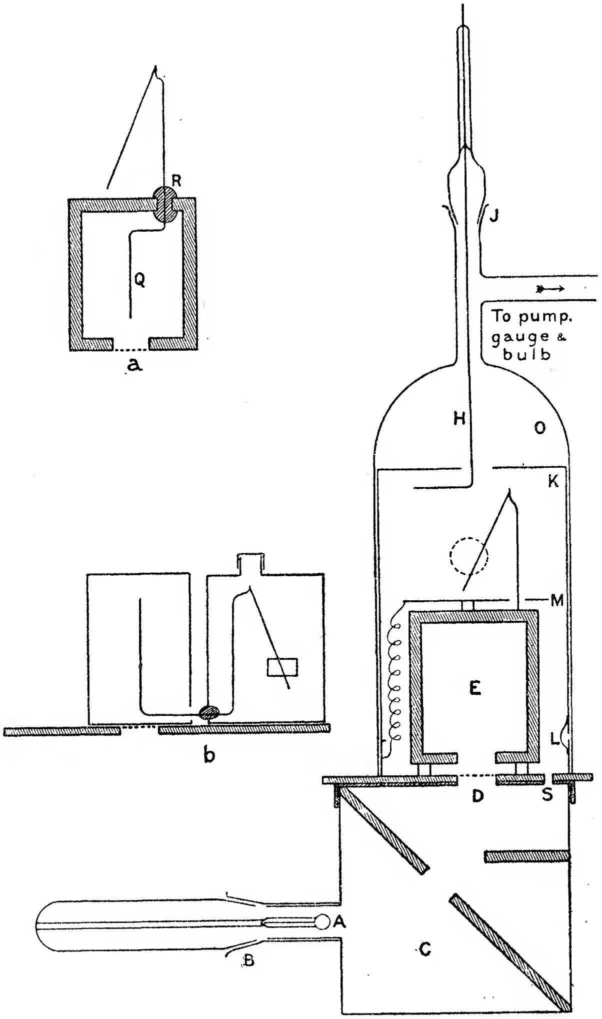

Fig. 1.

It was supported on three ebonite studs, and thus insulated. This method of catching the β-rays was adopted in order that the error due to the reflexion of the particles should be as small as possible, since only a small proportion of the reflected rays would be able to escape through the opening in the cylinder.

A standard to which a gold leaf was attached was carried by E, and the system could be charged by means of a rod H. This rod could be turned about a vertical axis, leakage of air into the apparatus being prevented by the ground glass joint J.

The gold-leaf system was surrounded by a brass tube K which screened it from electrostatic effects. This screen was joined to earth through a spring L. When the gold leaf was charged it was found to be unstable owing to the repulsion of the charge on E, and was therefore screened by means of an earthed plate M insulated from E by an ebonite plug.

The whole was enclosed in a glass vessel O, which was fastened with sealing wax to the lid of C, and could be exhausted along with the vessel C by a Fleuss pump. The final stage of exhaustion was carried out by means of a charcoal bulb immersed in liquid air. The pressure in the vessel was determined by means of a McLeod gauge, and was of the order 1/1000 mm. of mercury.

In performing an experiment the cylinder was first charged positively, and the rate of fall of the leaf determined. It was then charged to the corresponding negative potential and the rate of rise determined. The leaf was charged by means of a battery of 200 Clarke cells.

Now besides the negative charge gained by E due to the absorption of the β-particles, there is a leak of electricity from E to earth due to the ionisation in the residual air by the β-rays and the γ-rays from the source of radiation. In the first case the fall of potential of the leaf is due to the sum of the effects due to absorption and ionisation. In the second case the ionisation acts against the effect due to absorption, so that the mean of the two readings gives us the effect due to the absorption of the β-particles alone. Thus in an actual experiment the leaf fell with a velocity of 1·17 divisions per minute, when the vessel was charged positively, and rose with a velocity of 0·88 division per minute when it was charged negatively. The effect due to the β-particles alone, therefore, was 1·02 divisions per minute. This was repeated with the rays passing through magnetic fields of various strengths, so that the charge carried by the β-particles corresponding to the various velocities was determined. This charge is proportional to the number of particles entering the vessel, since each particle has the same electrical charge. The actual number of particles was not determined owing to the difficulty of measuring the capacity of the gold-leaf system.

The radius of curvature of the path of the rays was 3·5 cm. and the magnetic field was determined by means of a Grassot fluxmeter which was calibrated. The velocity was deduced from the product of the magnetic field and radius of curvature of the rays by means of the equations

$$\mathrm{H}\rho = \frac{mv}{e}, \qquad \frac{e}{m} = \frac{e}{m_0}\left(1 - \frac{v^2}{c^2}\right)^{\frac{1}{2}},$$

the latter being that required by the phenomena of relativity; where H is the value of the magnetic field, ρ the radius of curvature, v the velocity of the rays, and c the velocity of light. The value of e/m_0 was taken as $1{\cdot}74 \times 10^7$ E.M.U.*

To determine the ionisation due to the particles of different velocities the apparatus was modified as follows:—The cylinder E was removed and replaced by another of exactly the same size and shape, but which was connected to earth instead of being insulated (fig. 1*a*). A central rod Q was insulated from the vessel by a sulphur plug R, and carried a gold leaf by means of which the ionisation inside the vessel could be measured. The ionisation was determined at low pressures, viz., from 0·1 to 5 cm. of mercury, and was found to be proportional to the pressure. The opening was closed by a gold leaf in order to prevent the entrance of stray ions from the outside.

Now in these experiments the ionisation is increased by the reflexion of β-particles from the sides of the vessel. The amount of increase is different for different velocities, and a special experiment was made to determine the correction to be applied.

A cage of thin wire of the same size as the internal dimensions of the ionisation vessel was made as shown in fig. 1*b* and was covered with thin aluminium leaf. It stood on a plate of copper in which was a hole of the same size as that of E. This ionisation vessel was connected to an electroscope and the ionisation in it could be determined. A copper vessel of the same size as E but without bottom was made, and could be placed over the cage or removed at will. The proportional increase of ionisation when the copper vessel was on was found to be substantially the same as that determined for multiple reflexion between two plates by Kovarik and Wilson.† The results obtained could thus be corrected for the reflexion of particles from the sides of the vessel.

Results.

Experiments were made under two conditions. In the first experiments the hole D was closed by a thin sheet of mica covered with gold leaf. This was done in order to prevent spurious effects due to the ions formed in the vessel C being dragged into E by the electric field. A small hole S ensured the free passage of the air from C to O during exhaustion.

Results obtained are shown in Table I. It will be seen that the ionisation varies approximately inversely as the velocity for the lower velocities and as the square of the velocity for the higher.

---

* Bucherer, 'Phys. Zeit.,' 1908, vol. 9, p. 755.

† Kovarik and Wilson, 'Phil. Mag.,' November, 1910.

Table I.

$H\rho$. (Gauss cm.).	Velocity, v. 10^{10} cm./sec.	No. of β-particles (charge). Arbitrary units.	Ionisation.	Ionisation corrected for reflexion.	$\frac{\text{Ionisation}}{\text{Charge}} = \text{I}$.	$\text{I}v$.	$\text{I}v^2$.	$\text{I}v^3$.
770	1·24	66·0	22·5	22·5	341×10^{-3}	42	53	65
1060	1·56	90·0	29·5	25·0	278×10^{-3}	43	68	106
1350	1·85	104·0	32·5	23·9	230×10^{-3}	42	79	146
1650	2·20	112·0	33·5	22·0	196×10^{-3}	43	95	209
1940	2·25	116·0	33·0	20·5	163×10^{-3}	37	82	186
2180	2·36	119·5	31·2	18·8	157×10^{-3}	37	87	206
2440	2·49	119·5	29·0	17·0	142×10^{-3}	35	88	219
2710	2·54	116·0	26·5	15·2	131×10^{-3}	33	85	215
2980	2·60	109·0	24·2	13·7	126×10^{-3}	33	85	221
3240	2·66	101·0	22·0	12·4	123×10^{-3}	33	87	232
3500	2·70	94·0	20·0	11·3	120×10^{-3}	32	87	235
3720	2·72	88·5	18·3	10·3	116×10^{-3}	32	86	234
3960	2·75	82·0	16·5	9·3	113×10^{-3}	31	86	235
4630	2·81	68·5	12·7	7·2	105×10^{-3}	29	83	234
5420	2·86	53·5	9·6	5·6	105×10^{-3}	30	86	245
6300	2·90	41·0	7·8	4·8	117×10^{-3}	34	98	285

Now owing to the small charge carried by the rays it is impossible to work with very narrow pencils, and thus the rays sorted out are only approximately homogeneous. The error due to this would be especially marked for the very slow rays, since they are few in number, and the scattered β-particles of higher velocity which get into the vessel are thus relatively important. Further, we have seen that the hole D was closed by a mica window, and since the slow rays are very easily absorbed the proportion of swift to slow rays would be increased.

Thus, since the slow rays ionise more per centimetre of path than the swift rays, it follows that the ionisation for the rays corresponding to low magnetic fields will be less in proportion to the number of particles than it would be if the rays were more homogeneous and scattered rays were prevented from entering.

The apparatus was therefore modified as follows:—The mica was replaced by a thin gold leaf and the screens were altered so as to produce a better definition of the beam. This is the arrangement shown in fig. 1, and the results obtained are shown in Table II and graphically in fig. 2. The circles denote the experimental values, and the curves *a*, *b*, *c* are drawn on the assumption that the ionisation varies inversely as the first, second, and third power of the velocity respectively. It is at once apparent that the results agree much more closely with the second power law than with either of the others.

Table II.

Hρ. Gauss cm.	v. 10^{10} cm./sec.	No. of particles (charge).	Ionisation.	Ionisation corrected for reflexion.	$\frac{\text{Ionisation}}{\text{Charge}} = \text{I}$.	Iv.	Iv^2.	Iv^3.
850	1·35	49	7·67	7·67	15·7	21·2	28	38
1150	1·66	73	9·82	8·31	11·4	20·6	31	52
1390	1·87	87	10·99	8·10	9·3	17·8	32	61
1650	2·08	105	10·97	7·20	6·85	14·3	30	62
1890	2·23	106	10·47	6·50	6·14	13·7	30	71
2160	2·35	108	9·77	5·89	5·45	12·8	30	71
2440	2·46	102	8·64	5·06	4·95	12·2	30	74
2750	2·55	104	7·82	4·66	4·48	11·4	29	74
3300	2·67	89	6·44	3·63	4·08	10·9	29	78
3900	2·74	76	5·43	3·06	4·03	11·0	30	83
4800	2·82	56	3·82	2·16	3·86	10·9	31	87
5430	2·86	47	2·97	1·71	3·64	10·4	30	85
5910	2·88	44	2·58	1·52	3·46	9·9	29	83
6350	2·90	39	2·23	1·37	3·52	10·2	30	86

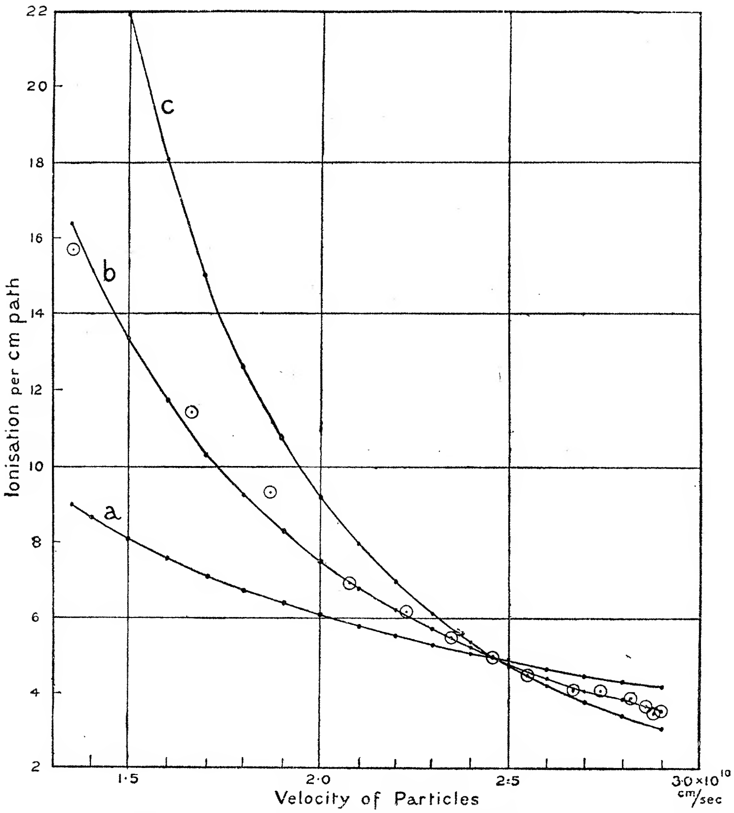

FIG. 2.—a is the curve $\text{I} = k_1/v$; b is the curve $\text{I} = k_2/v^2$; c is the curve $\text{I} = k_3/v^3$.

These results can be easily accounted for in the following manner.

Consider a large number of β-particles of velocity v passing through matter. The average time t spent by a particle in the neighbourhood of an atom is as $1/v$. Let the average force exerted on an electron in the atom by a β-particle be F. The distance moved by the electron in time t will be $\frac{1}{2}ft^2$, where f is the acceleration, and the work done will be $\frac{1}{2}\mathrm{F}ft^2$.

Now, if the same amount of energy is required for the production of each ion, the ionisation should be proportional to the work done by the β-particle, or to $\mathrm{A}t^2$, where A is some constant. Since t varies as $1/v$, the ionisation should vary inversely as the square of the velocity.

Ionisation in a Thick Copper Vessel.

Nearly all measurements of ionisation have been made with vessels thick enough to reflect a large proportion of the rays which fall on the walls, and the connection between the ionisation in the thick copper vessels used above and velocity is shown in Tables III and IV, which correspond respectively to the two sets of results given in Tables I and II. The values given in Table IV are shown graphically in fig. 3.

Table III.

$\mathrm{H}\rho$. Gauss cm.	v. 10^{10} cm./sec.	$\dfrac{\text{Ionisation}}{\text{Charge}} = \mathrm{I}$.	Iv.	Iv^2.
770	1·24	34·1	42	53
1060	1·56	32·8	51	80
1350	1·85	31·2	58	108
1650	2·20	29·9	66	144
1940	2·25	28·3	64	144
2180	2·36	26·1	62	146
2440	2·49	24·3	61	151
2710	2·54	23·2	59	150
2980	2·60	22·2	58	150
3240	2·66	21·8	58	152
3500	2·70	21·3	58	156
3720	2·72	21·6	59	160
3960	2·75	20·1	50	152
4630	2·81	18·6	52	147
5420	2·86	17·9	51	146
6300	2·90	19·0	55	160

We see that in this case the ionisation is not connected with the velocity by any simple power law. This is to be expected, on account of the complicated manner in which β-particles are scattered.*

---

* See Kovarik and Wilson, *loc. cit.*

Table IV.

Hρ. Gauss cm.	v. 10^{10} cm./sec.	$\frac{\text{Ionisation}}{\text{Charge}} = \text{I}$.	Iv.	Iv^2.
850	1·35	156	21	28
1150	1·66	134	22	40
1390	1·87	126	24	44
1650	2·08	104	22	45
1890	2·23	99	22	49
2160	2·35	90	21	50
2440	2·46	85	21	52
2750	2·55	75	19	49
3300	2·67	72	19	51
3900	2·74	71	19	53
4800	2·82	68	19	54
5430	2·86	63	18	51
5910	2·88	59	17	49
6350	2·90	57	16	48

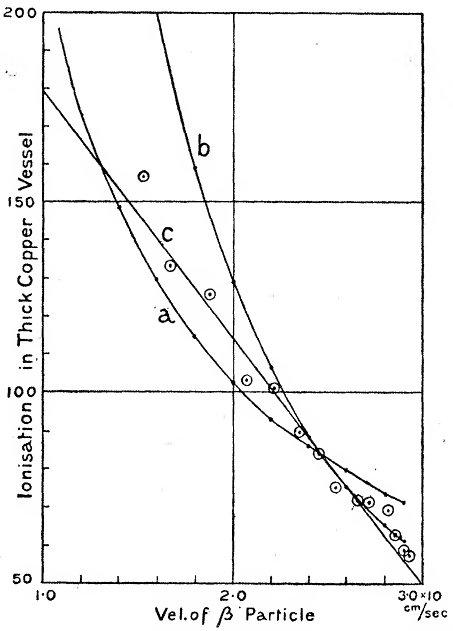

FIG. 3.—a is the curve $\text{I} = c_1/v$; b is the curve $\text{I} = c_2/v^2$; c is the curve $\text{I} = k_3'(c-v)$.

The ionisation under these circumstances, as will be seen from fig. 3, can, between the limits examined, be approximately represented by

$$\text{I} = k\,(c-v),$$

where I is the ionisation, v the velocity, c and k are constants.

Conclusions.

1. The ionisation produced per centimetre by β-particles in free air varies inversely as the square of the velocity between the limits examined.
2. The ionisation in a thick copper vessel is not connected with the velocity by any simple power law, but is approximately given by $I = k(c-v)$, where k and c are constants and v the velocity of the β-particles.

In conclusion, I wish to express my best thanks to Prof. Rutherford for proposing this research, and for his suggestions from time to time during its progress.

The Association of Lead with Uranium in Rock-Minerals, and its Application to the Measurement of Geological Time.

By Arthur Holmes, A.R.C.S., B.Sc., Imperial College of Science and Technology.

(Communicated by Prof. the Hon. R. J. Strutt, F.R.S. Received March 20,—Read April 6, 1911.)

1. *Introduction.*—The study of radioactive minerals is of great importance from two points of view. Such minerals may be regarded as storehouses for the various series of genetically connected radioactive elements. In them the parent element slowly disintegrates, while the ultimate products of the transformation gradually accumulate. The analysis of these minerals ought, then, in the first place, to disclose the nature of the ultimate product of each series; secondly, a knowledge of the rate of formation of this product, and of the total quantity accumulated, gives the requisite data for a calculation of the age of the mineral.

It has been shown that the disintegration of uranium results in the formation of eight atoms of helium.* In 1907 Boltwood brought forward strong evidence suggesting that lead is the ultimate product of this disintegration.† In this paper it is hoped to produce additional evidence that such is the case, according to the following equation:—

$$\begin{array}{ccc} U & \rightarrow\ 8He & +\ Pb. \\ 238{\cdot}5 & 32 & 2{\cdot}069. \end{array}$$

---

* See Strutt, 'Roy. Soc. Proc.,' A, 1908, vol. 81, p. 276.

† Boltwood, 'Am. Journ. Sci.,' 1907, p. 77.